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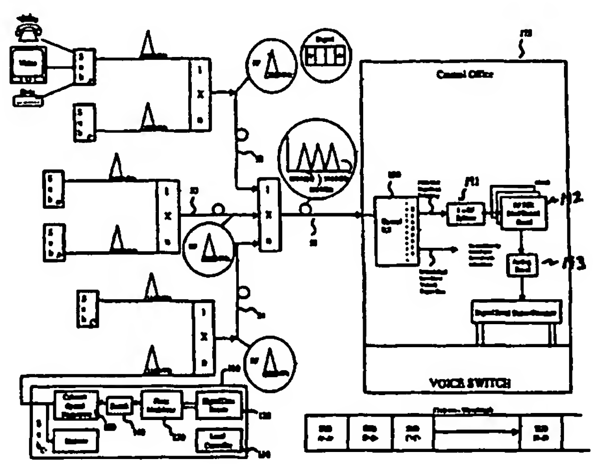
(54) Title: SYSTEM AND METHOD FOR TRANSMITTING A PLURALITY OF VOICE, DATA AND VIDEO SIGNALS OVER A PASSIVE OPTICAL NETWORK



(57) Abstract: A fiber optic communication system for transmitting signals from a plurality of spatially distributed subscriber transmitters to a central office. Each of the transmitters have a digital data source, a phase modulator, a coherent optical transmitter operating in continuous-wave mode and a biasing circuit to bias the coherent optical transmitter into its linear operating region, such that the coherent optical transmitter transmits light at a first wavelength, intensity modulated by the phase modulated data output within the linear operating region. Each transmitter may also be used to time division multiplex the actual data onto the fiber optic cable. Furthermore, the transmitters may also be grouped into a frequency division multiplexing scheme without the need for expansive, specifically-designed filters. The central office includes at least an optical receiver and phase demodulator. In a frequency division multiplexed scheme, the central office may also include the basic filter.

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System and Method for Transmitting a Plurality of Voice, Data and Video Signals Over a Passive Optical Network

Background of the Invention

1. Field of the Invention

The present invention relates in general to fiber optic communications and, in particular, to a system and method for combining a plurality of signals in a passive optical network using an analog-based time division multiplex access optical communication scheme.

2. Background Art

Transmission of data (voice, video and/or data) over fiber optic cabling is becoming common place. For instance, optical transmission is heavily used for long-distance (or inter-LATA) telephone transmission. Where fiber optic communication has been used in local exchanges (sometimes referred to as a Local Access & Transport Area or "LATA") a passive optical network (PON) has been used. The name PON arises from the use of passive splitters (e.g. star couplers) to distribute signal between the central office (CO) and multiple, spatially distributed subscriber locations via fiber optic cables.

There are a few basic types of fiber network architectures for LATA use, such as Fiber to the Node (FtTN) and Fiber to the Home (FTTH). In a FtTN system, signals are carried on fiber optic cable to a node in spatial proximity to a plurality of subscriber locations. Signals are converted from optical to electrical at the node and then carried from the node on twisted pair, copper wire and/or coaxial cable. In a FTTH system, signals are carried on fiber optic cable directly to each spatially distributed subscriber location. Fiber to the Home systems provide various advantages over the FtTN architecture including, but not limited to, lower initial cost of installed equipment (no common equipment required); choice of local or network powering; reduction in RF interference and cable loss; greater immunity to environmental effects such as heat, cold, precipitation, and humidity; an almost unlimited bandwidth; and a higher level of modularity to facilitate the provision of a better mix of customer services.

Accordingly it is an object of the present invention to provide a system that facilitates a Fiber to the Home architecture. In spite of the advantages of the Fiber to the Home architecture it is not without its potential disadvantages. For instance, the FTTH architecture requires an optical transmitter be located at each subscriber location which causes installed equipment costs to escalate. Thus, it is an associated object of the present invention to provide a system that facilitates the use of less expensive optical transmitters, while still providing an acceptable quality.

In FTTH and FtTN architectures used in the delivery of interactive communications (such as telephony and data), signals must be transmitted both "downstream" (i.e. from the CO to the subscribers) and "upstream" (from a subscriber to the CO).

The protocol for downstream communication is relatively simple because downstream communication has a single signal source (the CO) at which the signals can be multiplexed and/or uniquely addressed to each subscriber location. In fact, there are various known approaches to transmitting two or more signals over a single transmission channel, such as time division multiplexing (TDM), code division multiplexing (CDM), frequency division multiplexing (FDM) and wavelength division multiplexing (WDM). Most of these multiplexing schemes have been applied to the downstream portion of fiber optic communication systems. Nevertheless, in prior systems, FDM and WDM require expensive, custom-designed filtering and maintenance particularly as the number of communication channels increases.

The protocol for upstream communication is complicated by the spatial distribution of the signal sources, variations in the physical parameters of the optical transmitters, and noise from the plurality of optical sources, among other problems. In particular, advances in fiber optic communication involving merging optical signals have been constrained by the additive optical noise that results from combining multiple light sources at the same wavelength. Typically, the resulting Signal to Noise Ratio (SNR) is so low that the original transmitted data signal cannot be extracted and/or distinguished from the optical noise. Accordingly, it is an objective of the

present invention to combine multiple signals in a manner to sufficiently maximize the SNR such that the original data signals can be extracted for further processing.

Due to the aforementioned problems in upstream communication, the focus in prior art upstream protocols has been on the use of FDM and WDM in analog systems. The bandwidth of FDM, while significant, could be improved. Additionally, prior filtering schemes have been prohibitively complex. As for WDM, it would be prohibitively expensive to implement such a system with acceptable performance in an FTTH network

Other prior art approaches have experimented with the use of digital data under a TDM scheme. The prior TDM approach causes problems because in those systems the laser was powered up for each and every separate transmission time-slot assigned to that laser. Powering up the laser in this fashion greatly reduces the lifetime and reliability of the laser, as well as causing delays in the transmission of data because lasers require a finite amount of time to stabilize after power has been applied. Other TDM systems hold the laser at the extinction point, but those systems have an unacceptably low SNR, especially as the number of transmitters in the system increases.

Much, if not all, signaling in fiber optic communication systems is digital for the simple reason that digital signals have a higher noise immunity than analog signals, which made signal recovery more accurate. However, prior digital systems cannot transport CATV or cable modem signals without the use of WDM. Digital-based systems also have only one transmission stream whereas an analog-based scheme can support a large number of transmission streams. Additionally, digital-based schemes can have problems with dispersion (pulse spreading) depending on the bit rate and the length of the fiber.

As shown in Fig. 1 of the drawings, the current driving the laser has an almost exponential relationship to the laser's optical output power. The knee of this curve is referred to as the extinction point of the laser. Outside the area proximate the knee, CW lasers exhibit good linearity. In digital systems, the signal is switched between the

threshold current extinction point (digital 0) and some predetermined current above the extinction point chosen to provide a desired optical power (also shown in Fig. 1).

Thus, it is another object of the present invention to provide a communication scheme which minimizes the inrush current requirements of and raises the bit rate for the laser.

These and other objects will become apparent to those of ordinary skill in the art having the present specification, drawings and claims before them.

Brief Description of Drawings

Fig. 1 of the drawings is a graphical depiction of the operating characteristics of a standard laser used in fiber optic communications;

Fig. 2 of the drawings is a block diagram of the present system and method implemented in a "Fiber to the Home" ("FTTH") based network;

Fig. 3 of the drawings is a block diagram of a preferred embodiment of a customer premises interface;

Fig. 4 of the drawings is a block diagram of a preferred embodiment of the optical transmitter branch of a customer premises interface;

Fig. 5 of the drawings is a block diagram of a preferred embodiment of the optical receiver shown in Fig. 2; and

Fig. 6 of the drawings is a block diagram of a preferred embodiment of the RF receiver shown in Fig. 2.

Best Modes of Carrying Out the Invention

While the present invention may be embodied in many different forms, there is shown in the drawings and discussed herein a few specific embodiments with the understanding that the present disclosure is to be considered only as an exemplification of the principles of the invention and is not intended to limit the invention to the embodiments illustrated.

Fig. 2 of the drawings is a block diagram of the upstream aspect of the present system and method implemented in a "Fiber to the Home" ("FTTH") based network (as is preferred). As shown, system 100 facilitates transmission of a plurality of signals from a plurality of spatially distributed subscriber locations (sub A^1 . . . sub A^n; sub B^1 . . . sub B^n; sub C^1 . . . C^n) over fiber optic cables 51, 52, 53 and 54 to central office 175. In the present system, each subscribers' transmitter within system 100 transmit on the same optical wavelength (e.g. 1310 nm). In one preferred embodiment, the transmitters transmit during their assigned time slice with groups (e.g. A, B, C . . .(as shown in Fig. 2)) of n transmitters (at present, n equals 32 or less transmitters) also modulating their digital data about the same center frequency.

One embodiment implements a TDM scheme in which subscriber A^1 transmits a burst of data upstream in subframe A^1 and subscriber A^n transmits upstream in subframe A^n. Unlike a standard TDM scheme, however, the data transmitter, itself (coherent optical transmitter 150), is not turned off between its preassigned burst periods nor is the optical transmitter physically isolated from the optical fiber. Nevertheless, each RF transmitter section of each subscriber unit in each group (e.g. A^1 to A^n; B^1 to B^n; C^1 to C^n) are intended to be phase modulated about a single frequency, in turn, intensity (or amplitude) modulating the output of the optical transmitters, which output is combined by a group optical combiner onto a respective optical fiber (e.g. 52) and then combined onto the main fiber back (e.g. 51) to the central office.

In another embodiment of the present invention, the plurality of spatially distributed transmitters transmit in a FDM scheme that allows use of a less-complex filter. In one preferred implementation of this embodiment, the center frequencies about which the data is modulated are selected at 8 MHz intervals although the data channels themselves are only 6 MHz wide, thus, leaving a 2 MHz guard-band between adjacent channels. This approach minimizes RF spillover between channels and, in turn, further minimizes noise within the present system. So, for instance, in one preferred FDM embodiment, F_1=F_2=154MHz; F_3=F_4= F_1+8MHz =162MHz and F_5=F_6=F_3+8MHz=170MHz.

In a preferred embodiment, system 100 utilizes both the foregoing TDM and FDM schemes to facilitate the transmission of additional data through the network. In

each of these embodiments, at central office 175 (also known as a headend or CO), optical receiver 190 receives the multiplexed optical signals which are demodulated and the digital signal recovered for further processing by, for instance, a voice switch.

In each embodiment, the number of data sources utilized within the network can be increased while avoiding the expense and complexity of wavelength division multiplexing (WDM). In all embodiments, the present system utilizes an analog, rather than a digital optical encoding scheme. In a digital optical encoding scheme the laser output is biased to a predetermined point within its linear range and then is modulated between two currents, I_1 and I_2, on either side of this bias point and also within this linear range. Consequently, this approach also avoids the problems associated with laser inrush currents by maintaining the coherent optical transmitters in operation at all times, thus, providing the associated benefit of increased linearity even with a less expensive laser.

In all embodiments, voice, data and cable TV signals (or any one or a combination thereof) are transmitted between the plurality of subscribers and the central office completely on optical fiber. With the optical fiber available commercially, multimode fiber would only be reasonable to use in the present system over very short distances, and since the typical distance from any subscriber to the central office (or headend) often is on the order of miles, single-mode fiber is the preferred solution. While it is preferred to transmit all downstream communications on one fiber and all upstream communications on another, such a scheme is not necessary with the present system.

Preferably, the signals are received at and transmitted from the subscriber premises via a customer premises interface such as universal demarcation point 50, which was disclosed in Carlson et al., U.S. Patent No. 5,572,348, and assigned to the same assignee as the present invention (see Fig. 3). However, it is possible for other types of customer premises interface equipment to be utilized within the present system.

As shown in Fig. 2, each subscriber location includes a transmitter and receiver section. The transmitter section (controlled by local controller 110) includes digital

data source 120, phase modulator 130 with a predetermined center frequency, and coherent optical transmitter 150 directly driven by the phase modulated digital data. In the particular embodiment shown in Fig. 2, a TDM scheme can be used wherein switch 140 is controlled by local controller 110 such that coherent optical transmitter 150 receives (and, in turn, transmits) data only during its preselected time slot. Even under a TDM scheme the coherent optical transmitter remains on even outside its time slot, as noted above. In a FDM scheme, the transmitter circuitry shown in Fig. 2 -- exclusive of switch 140 -- may be used.

In one embodiment, the transmitter section is implemented on four layer boards with the ground planes on outer layers and the signal paths on the inner layers, thus the board shields the signals from ground plane noise. In addition, the power inputs may be filtered (as shown in Fig. 3) and thus the circuits are physically isolated from the power circuit.

Digital data source 120 may comprise any source of digital data such as voice or data. In a preferred embodiment, the digital data source continuously generates DS0 packets. Of course, as would be understood by those of ordinary skill in the art, other bit rates and the like are within the scope of the present invention and would result in minor design changes well within the ability of one of ordinary skill in the art having the present disclosure before them.

Various phase modulation techniques may be used in phase modulator 130 including, but not limited to: FSK (frequency-shift keying), BPSK (Binary Phase Shift Keying), QPSK (Quaternary Phase Shift Keying), ASK (Amplitude Shift Keying), OOK (on-off keying) and MSK (Minimum Shift Keying, an FSK derivative wherein minimum frequency spacing between two FSK signals (representing 0 and 1) allows coherent orthogonality such that the binary representations do not interfere with each other in the process of detection). One particular FSK phase modulation approach that represents a preferred approach for implementing the present system will be discussed below. However, inasmuch as the present invention can be used with any phase modulation technique and is not limited to the particular FSK modulation scheme (or VCO disclosed herein), those of ordinary skill in the art having the present specification

before them will be able to adjust the signal processing stages/parameters as a matter of design choice based on the implementation of the particular phase modulation scheme selected.

One embodiment of optical transmitter 200 of customer premises interface 50 is shown in Fig. 4. TXP is the digital data to be transmitted upstream. This digital data can take any format, such as NRZ and/or DS0 and is generated by a CODEC or other source of digital data as is known by those of ordinary skill in the art. As shown in Fig. 4, the digital data is fed into low pass filter 201, a gaussian filter design to remove high frequency energy from the incoming data stream. Low pass filter 201 has a passband rolloff similar to the raised cosine function that provides minimum intersymbol interference based on the Nyquist criterion (as those skilled in the art will recognize). In a preferred embodiment, the −3 dB frequency of filter 201 is set at about 2.5 MHz, corresponding to the bit rate of the data stream selected for this preferred embodiment. Such filtering is required regardless of the modulation method used, based on the Nyquist criterion. In a preferred embodiment, low pass filter 201 is implemented as a 4^{th} order all-pole design using discrete components. Of course, as would be known to those of ordinary skill in the art, this filter could also be implemented using any DSP capable of such configuration.

In a system using FSK modulation, the filtered data is preferably level adjusted by a potentiometer to adjust the modulation depth (i.e. the distance between the "ones" frequency and the "zeros" frequency). In a preferred embodiment, this potentiometer is a manually-tuned 5K Ohm potentiometer. It is also contemplated that a digitally controllable potentiometer could be utilized to allow for remote adjustment of modulation depth via the local controller. Of course, in a system using a different modulation scheme such as QPSK, such adjustment would be completely unnecessary.

The resulting signal is then passed through unity gain buffer 203, which is implemented in a preferred embodiment using an LT1010 unity-gain buffer IC from Linear Technologies of Miltpitas, California, which is biased with discrete components per the manufacturer's specification, as would be understood by one of ordinary skill in the art. Of course, any design that provides the desirable isolation between the filtering

stages and VCO 210 should be acceptable, as would be understood by one of ordinary skill in the art having the present disclosure before them.

In a preferred embodiment, the signal is then passed through pre-emphasis circuit 205, which, among other things, emphasizes the high frequency signals that remain at the edges of the data signal. Pre-emphasis circuit 205 is constructed from two resistors and two capacitors to improve the performance of VCO 210 and, thus, should be designed based on the selected VCO's modulation bandwidth characteristics and limitations. For instance, in a preferred embodiment, pre-emphasis circuit 205 is a high-pass, all-pole filter with a –3 dB frequency of 1.3 MHz and a very gradual rolloff in the stopband.

In the disclosed embodiment using FSK modulation, the output of pre-emphasis circuit 205 is fed into summer 206, which is comprised of this pre-emphasis filter in combination with a capacitor to ground, and a series resistor connecting the output of op amp 209. Op amp 209 is used to boost the output voltage of PLL 207 to fully utilize the range of frequencies that VCO 210 is capable of generating.. The other input to summer 206 is the Phase Detector output of PLL 207, which keeps the VCO center (or average) frequency locked to the reference frequency internally-generated by the PLL.

VCO 210 can be any standard voltage-controlled oscillator with a modulation bandwidth of approximately half the bit rate range. This bit rate range is dependent, in part, on the number of DS0 channels implemented. In a preferred embodiment, VCO 210 is a JTOS 300 by Mini-Circuits of Brooklyn, New York with a wider modulation bandwidth being accomplished by replacing the standard input capacitance with a 68 pF NPO style capacitor to accommodate a 2.56 Mbit channel. By increasing the modulation index of the VCO the SNR is increased which allows a high data rate, in turn facilitating traffic from more signal sources on the same fiber network.

The feedback path from VCO 210 is connected to the frequency input of PLL 207, a controllable phase-locked loop whose reference frequency is derived, in a preferred embodiment from a local 4 MHz crystal with a temperature coefficient of 100 ppm over the whole temperature range. In particular, the reference frequency has been chosen (as a matter of design choice) to be 25 kHz. Based on this reference frequency

and crystal selection, an internal divider count of 160 is implemented to achieve the desired reference frequency.

Phase detector output of PLL 207 is fed into low-pass filter 208. Preferably, low-pass filter 208 is a lag-lead filter with a very long time constant on the order of 150 msec. The long time constant serves to smooth out any minor output variations, thus tending to maximize stability of the oscilator. The output of low-pass filter 208 is fed into op-amp 209. Op-amp 209 provides gain so as to extend the range of VCO 210. In the particularly disclosed embodiment, the output of PLL 207 would only utilize about half of the range of VCO 210, thus, op-amp 209 provides a gain of 2 to allow utilization of the complete range of the particularly selected VCO. In a preferred embodiment, op-amp 209 is an AD820 op amp from Analog Devices of Norwood, Massachusetts. No biasing of this commercially-available op amp is needed. This op amp was chosen to have good power supply noise rejection, very low noise at its output and rail-to-rail characteristics; yet, these characteristics are not particularly required. The output of op-amp 209 is fed into summer 206 to complete the feedback loop of VCO 210.

Via the feedback path, the center frequency of VCO 210 is determined by PLL 207. In a preferred embodiment, this center frequency is selected to be between 154 MHz and 290 MHz in 8 MHz steps as instructed by the local controller, perhaps in response to instructions from the headend controller. Of course, the selection of particular frequency ranges is a matter of design choice dictated by the use of the upstream frequencies for other purposes (e.g. video set top box and cable modem channels).

In this preferred embodiment, PLL 207 is a MC 145190 manufactured by Motorola Corporation of Schaumburg, Illinois, which has a serial data port that allows adjustment of the PLL's output frequency. In particular, the PLL is controlled via a SPI Bus interface that is directly driven by the local controller through a filter circuit. Specifically, the Motorola PLL utilizes the following information:

- C Register – these bits control how the PLL features are set. In one design approach, the C Register is set as follows:

C7 (Polarity of PD) - set LOW, polarity not inverted.

C6 (PD A or B) - set HIGH, select PD A.

C5 (Lock Detector enable) - set HIGH, even though lock detector is not used.

C4 (Standby bit) - set LOW, no standby mode.

C3, C2 (PD source/sink current bits) - set both HIGH to provide maximum current.

C1 (port bit) - set LOW, PD step size is 10%.

C0 (Output B state) - set HIGH, for high output impedance.

- Counter and Register provisioning – based on a reference frequency of 25 KHz, giving a minimum step size of 25 KHz. They are determined by the formula Fin = Fref*(N*64+A).

Fstep **25000** **PLL Register Data**

Tx Freq (MHz)	Divisor (TxFreq /Fstep)	N Counter	A Counter	R Counter	C Register	bits 23-16	A Register bits 15-8	bits 7-0	R Register bits 15-8	bits 7-0
154	6160	96	16	160	6D	B0	60	10	20	A0
162	6480	101	16	160	6D	B0	65	10	20	A0
170	6800	106	16	160	6D	B0	6A	10	20	A0
178	7120	111	16	160	6D	B0	6F	10	20	A0
186	7440	116	16	160	6D	B0	74	10	20	A0
194	7760	121	16	160	6D	B0	79	10	20	A0
202	8080	126	16	160	6D	B0	7E	10	20	A0
210	8400	131	16	160	6D	B0	83	10	20	A0
218	8720	136	16	160	6D	B0	88	10	20	A0
226	9040	141	16	160	6D	B0	8D	10	20	A0
234	9360	146	16	160	6D	B0	92	10	20	A0
242	9680	151	16	160	6D	B0	97	10	20	A0
250	10000	156	16	160	6D	B0	9C	10	20	A0
258	10320	161	16	160	6D	B0	A1	10	20	A0
266	10640	166	16	160	6D	B0	A6	10	20	A0
274	10960	171	16	160	6D	B0	AB	10	20	A0
282	11280	176	16	160	6D	B0	B0	10	20	A0
290	11600	181	16	160	6D	B0	B5	10	20	A0

In a TDM system, the output of the phase modulator (in the disclosed embodiment, VCO 210) is operably provided to RF switch 211 and an attenuation network 212 upstream of the laser to substantially preclude RF signal leakage to the

laser during the intended inactive periods for that particular transmitter. Attenuation network is implemented based on the particularly selected laser. In a preferred embodiment, attenuation network 212 has a 8 dB pad. RF switch 211 is controlled by TXENP to provide data during the time-slot assigned to the particular transmitter. Attenuation network 212 is followed by RF amplifier 213 providing 11 dB gain, thus, resulting in a total gain of 3 dB between the output of VCO 210 and the laser. The 3 dB was determined to be desirable in a preferred embodiment such that the signal can modulate the laser at a high enough current to ensure stimulated emissions in the linear range beyond the laser's threshold current. Thus, as would be understood to those of ordinary skill in the art, the desired gain is dependent on the conversion efficiency of the particular laser used.

In all embodiments, the FM phase modulated voice data is fed into a passive RF equalizer. The RF equalizer used to compensate the frequency dependence of the VCO output level is designed with 4 passive L-C resonant components in a standard equalizer configuration used in most CATV systems. It was designed to provide extra attenuation needed at lower frequencies and a high frequency passband for minimal loss. Attenuated signals are not terminated with a resistive component but reflected back through the input of the equalizer.

In the embodiment shown in Fig. 4, the transmitter circuitry includes a separate branch for passing through data without any additional phase modulation. This path may be used, for instance, in transmitting upstream RF modulated video signals (for instance in a NTSC format) or for a "cable-modem." In the particular embodiment shown, the data from this source is fed into low-pass filter 214 to substantially remove any high frequency energy above 70 MHz. This low-pass filter is a pole-zero type with a pole in the stop band and a substantially constant group delay in the passband. The low-pass filter can be implemented using discrete components or by programming a DSP to achieve the desired processing. The output of low-pass filter 214 is fed into RF amplifier 215. In a preferred embodiment, RF amplifier has a gain of approximately 11 dB and provides isolation between the phase modulated data and this upstream data.

In an embodiment having this alternative "pass-through" branch, the amplified pass-through data (output by RF amplifier 215), as well as the amplified, phase modulated data (output by RF amplifier 213) are fed into summer 220. Of course, in an embodiment that does not include this alternative "pass-through" branch no combiner would be necessary.

The data is fed into transformer 221, which is used to provide an impedance step-down of 4:1. Thus, in a preferred embodiment using a laser having an input impedance of 3 to 8 Ohms, the combiner sees an impedance of 12 to 32 Ohms. This impedence matching allows the greatest power transfer to the laser, thus, increasing the signal to noise ratio.

In a preferred embodiment of the present invention coherent optical transmitter 150 includes laser 250 which is a Fabry-Perot laser model number A370-10 manufactured by Lucent Technologies Microelectronics Group of Allentown, Pennsylvania. Laser 250 is driven by the current output by summer circuit 251, which receives the modulated data to be transmitted across the fiber as well as a DC offset signal generated by laser bias controller 252 based on feedback from laser monitor 253 and a selected adjustment (indicated in the figure as laser bias adjustment 255).

In one embodiment, summer circuit 251 receives another input from pilot signal source 260 having a pilot signal frequency, said pilot signal frequency being outside a range of frequencies utilized by data within the system (for instance less than 5 MHz). This pilot signal directly modulates the laser continuously thereby further minimizing any noise introduced by that particular laser on the telephone network, as a whole. As known in the art, the pilot signal source could be a low frequency oscillator or other frequency generator.

In a preferred embodiment, laser bias controller 252 is implemented with an IC (MAX 3766 manufactured by Maxim Integrated Products of Sunnyvale, California), which is normally used as a 622 MHz digital baseband driver. As noted above, it is configured in the present system to set the DC output level of laser 250. In addition, the driver can be used to send the local controller a signal when the laser output is beyond control or has died completely and, consequently turns the laser off in response

to a signal from the local controller. This external on/off control is necessary with the particularly selected Fabry-Perot laser of the disclosed embodiment because the power switch integrally associated with that laser must be isolated to minimize noise in the laser's optical output. Laser monitor 253 is – using the preferred laser – integral with the laser diode package.

No special optical isolation of the laser output is necessary. However, care should be taken to avoid reflection, as reflected signals may ultimately retransmit as noise. Avoidance of reflection may be accomplished by ensuring sufficient optical loss before the first "optical bend." Alternatively, using an angle-polished connector (APC), fusion splicing the upstream cable into the combiner; or ultra polished connector (UPC) in combination with an attenuator would sufficiently minimize reflection.

It is also possible to add optical isolation to the output of the laser. For instance, with the Lucent Fabry-Perot A370-10 Laser a PIFI53PS11133 optical isolator manufactured by E-TEK Dynamics of San Jose, California could be used. In another approach a Distributed Feedback Laser (DFB) laser with integrated isolation could be used, such as Lucent's A371-10. Of course, use of an optical isolator or a DFB laser would increase the cost of the system.

Basically, the present system has been designed to accommodate the use of inexpensive, low-powered coherent optical transmitters given the large number of optical transmitters necessary in a true FTTH network. This can be accomplished by doing one or more of the following: (1) minimizing RF noise by providing significant guard bands and selecting more robust encoding schemes; (2) minimizing optical noise by (a) when not actively transmitting, modulating the laser with a pilot signal outside signal frequency and (b) maximize the isolation of the laser from the RF modulated signal outside of the assigned time slot); (3) increasing optical signal strength; (4) increasing the amount of useful energy; (5) utilization of an analog signal. Nevertheless, as would be understood by one of ordinary skill in the art, it is possible to utilize more expensive, power-needy lasers within the present system. In either event, an acceptable coherent optical transmitter in the present implementation would have to

have extremely linear characteristics, although this is not implicit in the system-level concept. In order to keep the power requirements low, a low-power laser (about 1 mW) is used. Over time, as efficiencies of commercially available lasers increase, this parameter will become less important.

Fig. 5 of the drawings is a block diagram of optical receiver 190 at the central office. As shown in Fig. 5, the composite optical signal is received from multiple spatially distributed transmitters by photodetector 301, which converts the optical signal into an electrical signal. Photodetector 301 must exhibit good linearity and sensitivity and may comprise either a Lucent 131AT by Lucent Technologies of Allentown, Pennsylvania or a Mitsubishi FO-15PD-N by Mitsubishi Electronics America of Sunnyvale, California. Good sensitivity provides a better signal to noise performance, which is important because the majority of noise in the system will be contributed by the photodetector, itself. Good linearity results in a minimization of distortion levels and sidebands and spurs created by the photodiode. In a preferred embodiment, photodetector 301 is powered through back biasing circuit 302. Back biasing circuit 302 is configured such that if the received optical signal is too strong or too, weak, or photodiode 301 malfunctions, a red light is illuminated in back biasing circuit 302, otherwise a green light is illuminated. Of course, it is also possible to merely provide the current and voltage nominally required by photodiode 301 for operation within the present system.

In the present system, if there is greater than a 3dB difference between the optical levels of the plurality transmitters received by photodetector 301 (which translated to a greater than 6dB difference in RF levels), an unacceptable noice floor occurs resulting in increased bit errors. While this may be tolerable in voice transmission, these bit errors would require forward error correction in any data transmission. By increasing the overall optical level at the receiver, the permissible difference without creating an unacceptable SNR widens. The optical level can be increased in the present system by doing one or more of: (1) making photodetector 301 more sensitive; (2) tightening network design rules; and (3) power leveling in the RF and/or optical domain.

In a preferred embodiment of the present invention, the system includes a "slow power-up circuit," which allows the voltage applied to the various components to ramp up in a predictable manner. A "slow power up circuit" is important in a system allowing the hot plug-in of components.

The electrical signal output from photodetector 301 is fed into RF amplifier 305, a class A amplifier which has a gain of 11 dB. By utilizing a class A amplifier, distortion can be kept at a lower level, however, the power needs will increase. In a preferred embodiment, the output of RF amplifier is connected to DC blocking capacitor, preferably a NPO-type capacitor at 1000 pF nominal. In a preferred embodiment having the signal pass through path in the subscriber units, the output of DC blocking capacitor is operably connected to a 1-to-2 RF splitter 307 and, in turn, to low pass filter 309 and high pass filter 310. Both the low pass filter 309 and high pass filter 310 have 4 poles, with substantially flat delay characteristics in their respective passbands. The low pass filter 309 rolls off above 70 MHz and the high pass filter 310 rolls off below 130 MHz. The 2:1 RF splitter 307, in combination with low pass filter 309 and high pass filter 310, allows low frequency data such as video and digital modem data to be separated from high frequency telephony data, coming to the CO from the downstream subscribers. In a preferred embodiment, the high band path (preferred band is 150MHz to 300MHz) is for telephony channels only. The unmodulated low frequency (i.e., preferably 5-40 MHz) is combined at the CO (combiner circuit not shown in Fig. 5) with other unmodulated low frequency data from the plurality of downstream subscribers. The combined unmodulated low frequency data (i.e. video and digital modem data from subscribers) is also combined at CO with CATV signals for routing downstream to subscribers.

Fig. 6 of the drawings is a block diagram of demodulation circuit section 400 of RF FSK Mod/Demod 192 at the central office. As shown in Fig. 6, the demodulation circuit section 400 demodulates the upstream serial telephony bitstream coming from the high-band pass filter 310 of the optical receiver 190. Tuner module 401 (which may be a Temic 4732PYS manufactured by Temic Multimedia Component Inc. of Irving, Texas) is configured through the I^2C Bus interface to convert the FSK signal frequency to an Intermediate Frequency (IF) of 43.75 MHz. This is passed through

SAW bandpass filter 402 (preferably a X6964M manufactured by Siemens-Matsushita Components of Munich, Germany), which has a center frequency of 43.75 MHz and a 3 dB bandwidth of 6 MHz to remove any other mixing products, then through two FM demodulator chips (preferably MC 13155, manufactured by the Motorola Corporation of Schaumburg, Illinois), the first (i.e., IF amplifier 403) of which is used only for RF amplification. The second FM demodulator (i.e., FM wideband detector 404) is used as an RF amplifier and as the demodulator stage.

The SAW filter 402 has a center frequency of 43.75 MHz and a 3 dB bandpass of 6 MHz. The IF frequencies of the FSK signal sit at 43.75 MHz when the tuner module is provisioned correctly, and vary ∓1.28MHz around that frequency. Most of the energy is well within the 6MHz passband of the filter. The insertion loss of the SAW filter is about 15 dB. The purpose of the first FSK demodulator IC 403 is simply to act as a 46 dB amplifier of the IF signal.

The second FSK demodulator IC 404 also has 46 dB of RF amplification. This much amplification is needed since the SAW filter has 15 dB of insertion loss, and the fiber-optic network attenuates the RF signal 2 dB for every 1 dB of optical attenuation. This could result in about 40 dB of RF attenuation just through the fiber-optics.

The FSK demodulator 404 performs a Frequency-to-Voltage conversion on the incoming telephony signal converting it back to a bit stream. This is accomplished in a preferred embodiment with the aid of an external tuned-tank circuit (tank circuit not shown in Figure 6) feeding a quadrature detector. In some embodiments, a resistor is placed across the tank to reduce the Q of the circuit. This resistor must be a calculated value to accommodate the required bandwidth of the FSK signal. The Q of the tank is 7.3 which gives a bandwidth of 6 MHz at the 43.75 MHz IF frequency.

The only adjustment on the FSK receiver section is of the tuned tank circuit. Those skilled in the art will understand that the tank circuit must be tuned so that the high (1's) frequency will cause 0° phase shift across the tank and the low (0's) frequency will cause almost a 90° phase shift across the tank. A quadrature detector in the IC recovers the data from this orthogonal data. This adjustment balances the

outputs and provides a more robust signal with a proper duty cycle at the comparator single-ended output.

The outputs of the FSK demodulator IC 404 are connected through an RC low-pass filter (not shown in Figure 6 of the disclosed embodiment) to the high-speed comparator 405. That FSK demodulator output (from the tuner and through the two demodulators) is a differential output which suppresses common-mode signals, reduces emitted EMI, provides better phase linearity, and enhances RF stability. The high-speed comparator 405 converts the differential output of the demodulators to a single-ended signal. In a preferred embodiment using MAX 999 manufactured by Maxim Integrated Products of Sunnyvale, California, there is a small amount of hysteresis built into high speed comparator 405, otherwise it would have been desirable to add such hysteresis externally. In a preferred embodiment, an RC filter on the single-ended output reduces any unwanted noise. This upstream serial digital telephony bitstream signal is output from the receiver to analog board 193 where the upstream telephony serial data is demultiplexed for further processing.

In a preferred embodiment of the present system, downstream interactive (i.e. data and voice) communication is transmitted using the same scheme disclosed with respect to the upstream system. It should be noted, however, that any of the known communication schemes will work in the downstream path (so long as they do not interfere with the upstream scheme) without departing from the present invention.

The foregoing description and drawings merely explain and illustrate the invention and the invention is not limited thereto. Those of the skill in the art who have the disclosure before them will be able to make modifications and variations therein without departing from the scope of the present invention.

For instance, the group lettering scheme used to designate subscribers has been used herein merely to explain the principles of the present invention. It will be readily understood by those skilled in the art that in one possible alternative embodiment members A1, B1 and C1 could transmit at the same frequency, but in different time slots. Similarly, group members could be physically interspersed amongst each other.

WHAT IS CLAIMED IS:

1. A system for transmitting a plurality of signals from a plurality of spatially distributed subscriber locations over a fiber optic cable to a central office, said system comprising:

- a plurality of subscriber transmitters each being associated with a particular subscriber location and operably connected to said fiber optic cable, each of said subscriber transmitters including:

  a source of digital data,

  a phase modulator operably receiving said digital data and having a phase modulated output,

  a coherent optical transmitter operably connected to said fiber optic cable, said coherent optical transmitter operating in continuous-wave mode and having a substantially linear operating region at least above said coherent optical transmitter's threshold current, said coherent optical transmitter transmitting light at a first wavelength, said light being intensity modulated by at least said phase modulated output within said linear operating region, and

  a biasing circuit operably connected to said coherent optical transmitter to bias said coherent optical transmitter into said linear operating region;

- an optical receiver associated with said central office operably connected to said fiber optic cable; and

- a phase demodulator operably connected to an output of said optical receiver.

2. The invention according to Claim 1 wherein each of said subscriber transmitters further includes a switch operably connected between said phase modulated output and said coherent optical transmitter, signal transmission through said switch being controlled by a controller such that said coherent optical transmitter transmits data only during a time slot selected for said subscriber transmitters associated with that coherent optical transmitter.

3. The invention according to Claim 2 wherein said controller is local to each of said transmitters.

4. The invention according to Claim 2 wherein said controller is located in the central office.

5. The invention according to Claim 2 wherein said phase modulator in each of said subscriber transmitters implements a frequency modulation scheme, each of said plurality of subscriber transmitters being assigned a center frequency within a range of frequencies, such that each subscriber transmitter has a combination of said center frequency and said time slot such that it is unique from every other transmitter.

6. The invention according to Claim 5 wherein each of said transmitters further includes a pilot signal source having a pilot signal frequency, said pilot signal frequency being outside said range of frequencies utilized by data within the system, said pilot signal source directly modulating said coherent optical transmitter substantially continuously.

7. The invention according to Claim 2 wherein each of said transmitters further includes a pilot signal source having a pilot signal frequency, said pilot signal frequency being outside a range of frequencies utilized by data within the system, said pilot signal source directly modulating said coherent optical transmitter substantially continuously.

8. The invention according to Claim 1 wherein said phase modulator in each of said subscriber transmitters implements a frequency modulation scheme, each of said plurality of subscriber transmitters being assigned a unique center frequency.

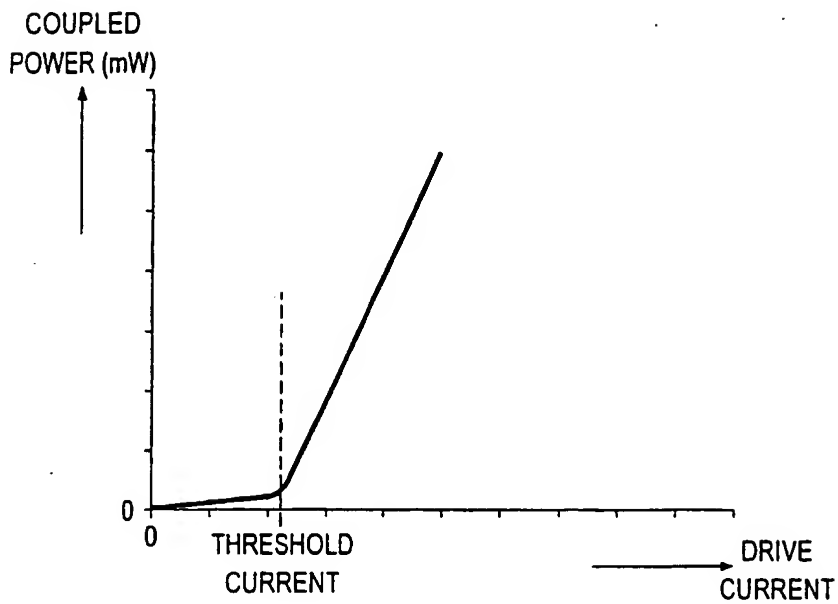
9. The invention according to Claim 1 wherein said source of digital data includes a low pass filter and a preemphasis filter.

10. The invention according to Claim 1 wherein said modulator and demodulator utilize a frequency modulation scheme.

12. The invention according to Claim 1 wherein said coherent optical transmitter includes a Fabry-Perot laser.

13. The invention according to Claim 1 wherein each of said transmitters further includes a pilot signal source having a pilot signal frequency, said pilot signal frequency being outside a range of frequencies utilized by data within the system, said pilot signal source directly modulating said coherent optical transmitter substantially continuously.

FIG. 1



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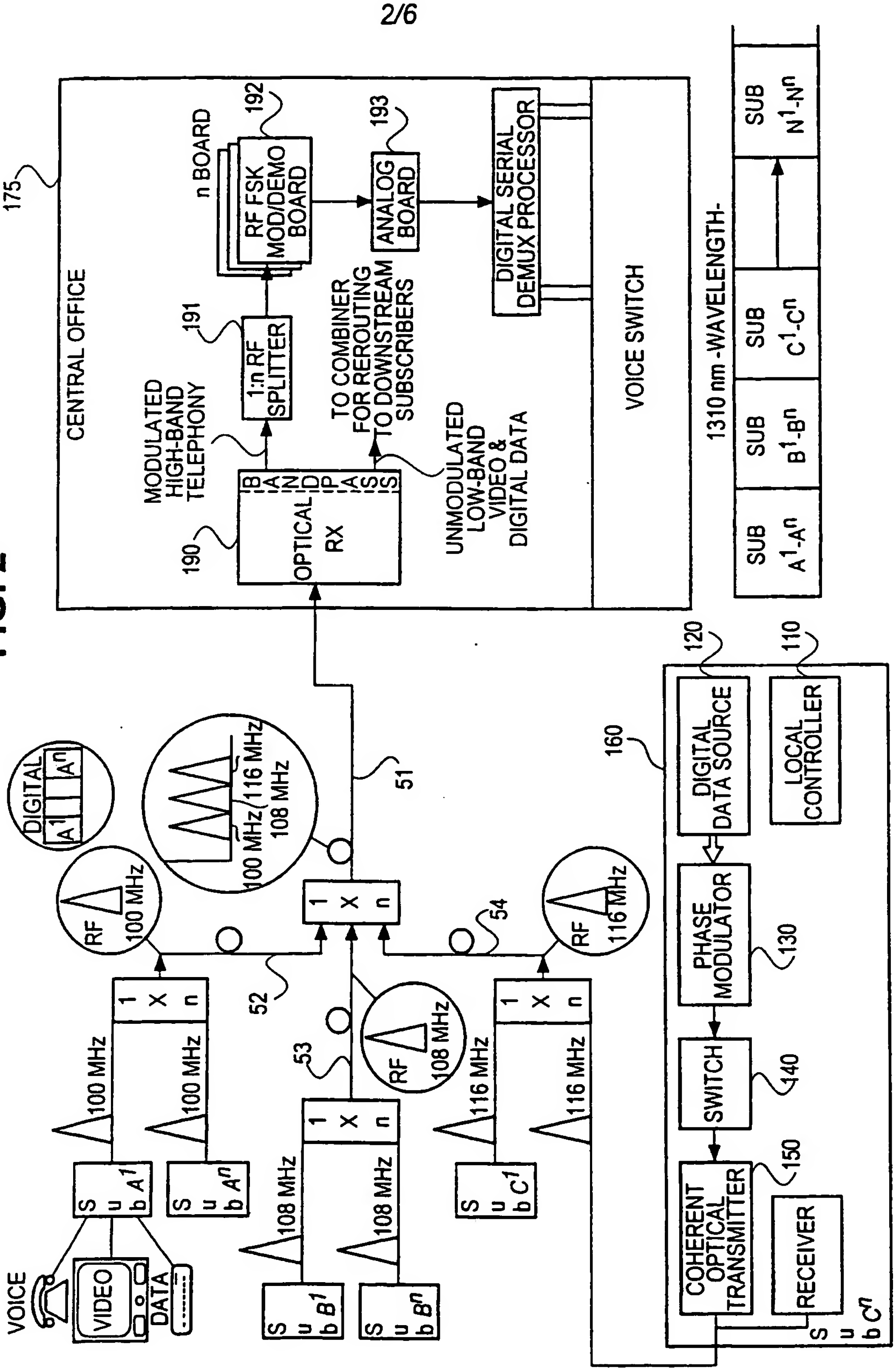


CENTRAL OFFICE
175
OPTICAL RX
190
MODULATED HIGH-BAND TELEPHONY
1:n RF SPLITTER
191
RF FSK MOD/DEMO BOARD
n BOARD
192
ANALOG BOARD
193
DIGITAL SERIAL DEMUX PROCESSOR
TO COMBINER FOR REROUTING TO DOWNSTREAM SUBSCRIBERS
UNMODULATED LOW-BAND VIDEO & DIGITAL DATA
BANDPASS
VOICE SWITCH
1310 nm -WAVELENGTH-
SUB A1-An
SUB B1-Bn
SUB C1-Cn
SUB N1-Nn
VOICE
VIDEO
DATA
Sub A1
Sub An
Sub B1
Sub Bn
Sub C1
Sub Cn
100 MHz
108 MHz
116 MHz
1 X n
RF
DIGITAL
A1
An
100 MHz
116 MHz
108 MHz
51
52
53
54
160
DIGITAL DATA SOURCE
120
LOCAL CONTROLLER
110
PHASE MODULATOR
130
SWITCH
140
COHERENT OPTICAL TRANSMITTER
150
RECEIVER

FIG. 2

FIG. 3

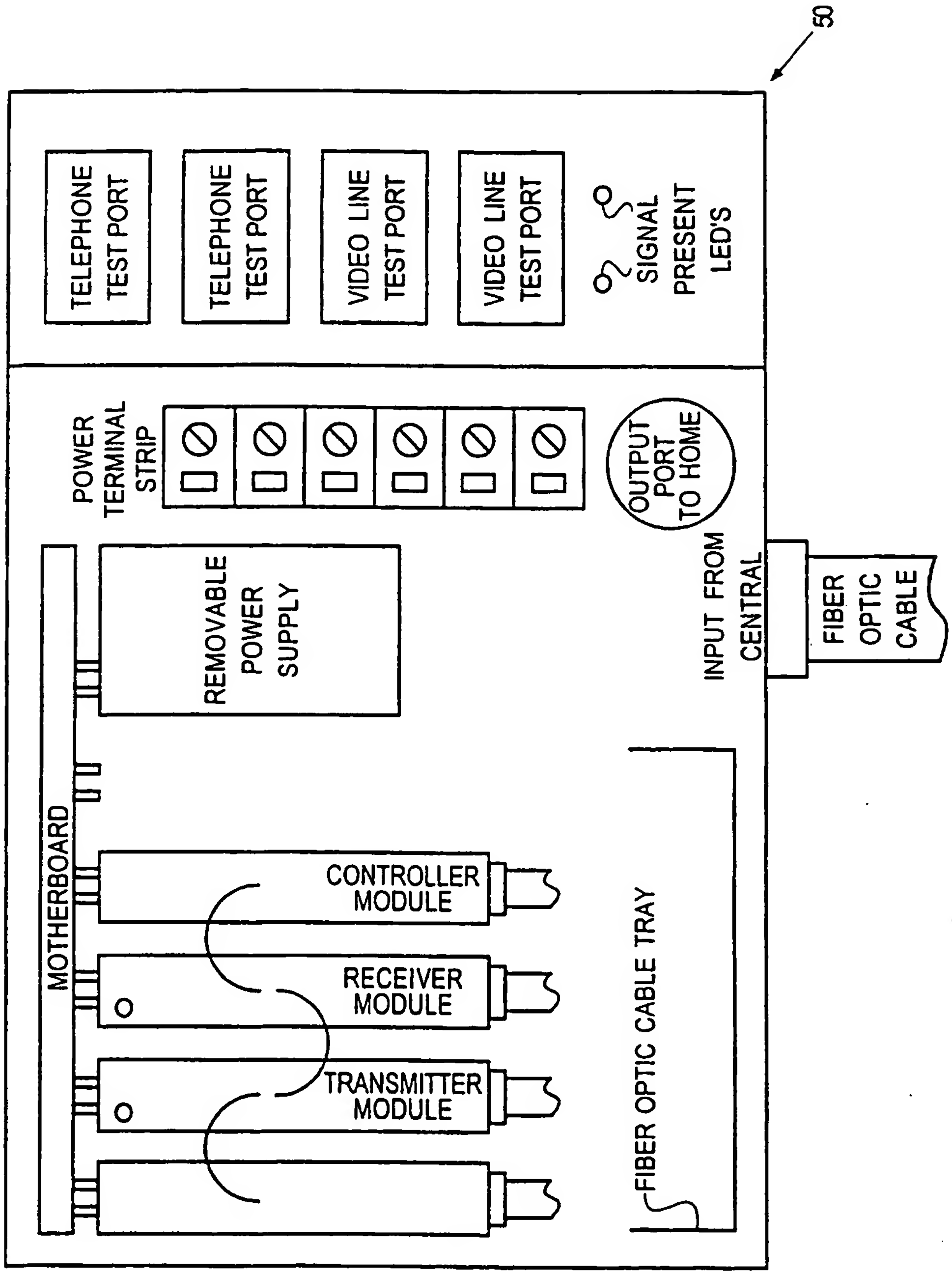

50
TELEPHONE TEST PORT
TELEPHONE TEST PORT
VIDEO LINE TEST PORT
VIDEO LINE TEST PORT
SIGNAL PRESENT LED'S
POWER TERMINAL STRIP
OUTPUT PORT TO HOME
INPUT FROM CENTRAL
FIBER OPTIC CABLE
REMOVABLE POWER SUPPLY
MOTHERBOARD
CONTROLLER MODULE
RECEIVER MODULE
TRANSMITTER MODULE
FIBER OPTIC CABLE TRAY

FIG. 4

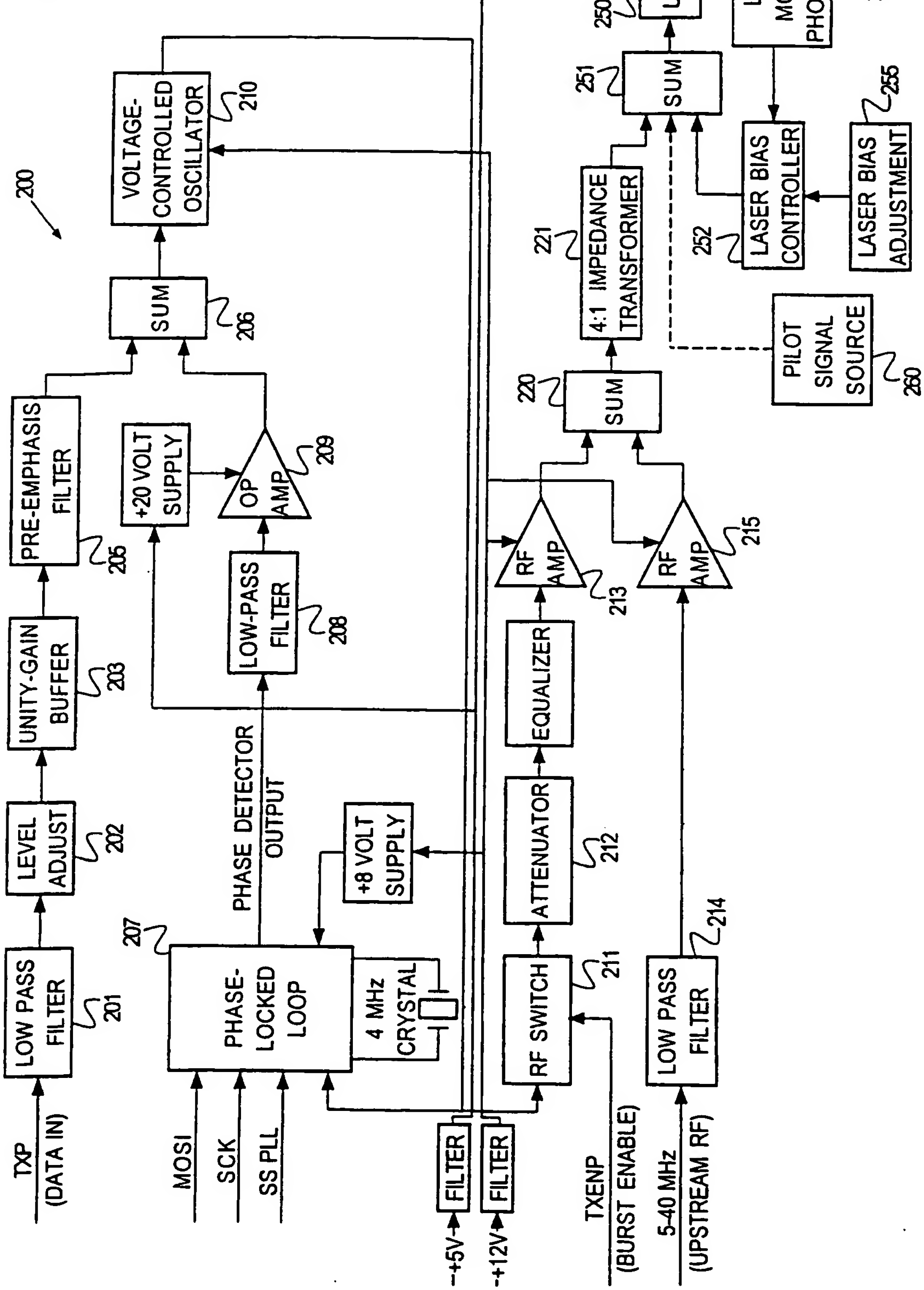

200
TXP (DATA IN)
LOW PASS FILTER
201
LEVEL ADJUST
202
UNITY-GAIN BUFFER
203
PRE-EMPHASIS FILTER
205
SUM
206
VOLTAGE-CONTROLLED OSCILLATOR
210
MOSI
SCK
SS PLL
PHASE-LOCKED LOOP
207
4 MHz CRYSTAL
+8 VOLT SUPPLY
PHASE DETECTOR OUTPUT
LOW-PASS FILTER
208
OP AMP
209
+20 VOLT SUPPLY
+5V
+12V
FILTER
FILTER
TXENP (BURST ENABLE)
RF SWITCH
211
ATTENUATOR
212
EQUALIZER
RF AMP
213
5-40 MHz (UPSTREAM RF)
LOW PASS FILTER
214
RF AMP
215
SUM
220
4:1 IMPEDANCE TRANSFORMER
221
PILOT SIGNAL SOURCE
260
SUM
251
LASER
250
LASER MONITOR PHOTODIODE
253
LASER BIAS CONTROLLER
252
LASER BIAS ADJUSTMENT
255

FIG. 5

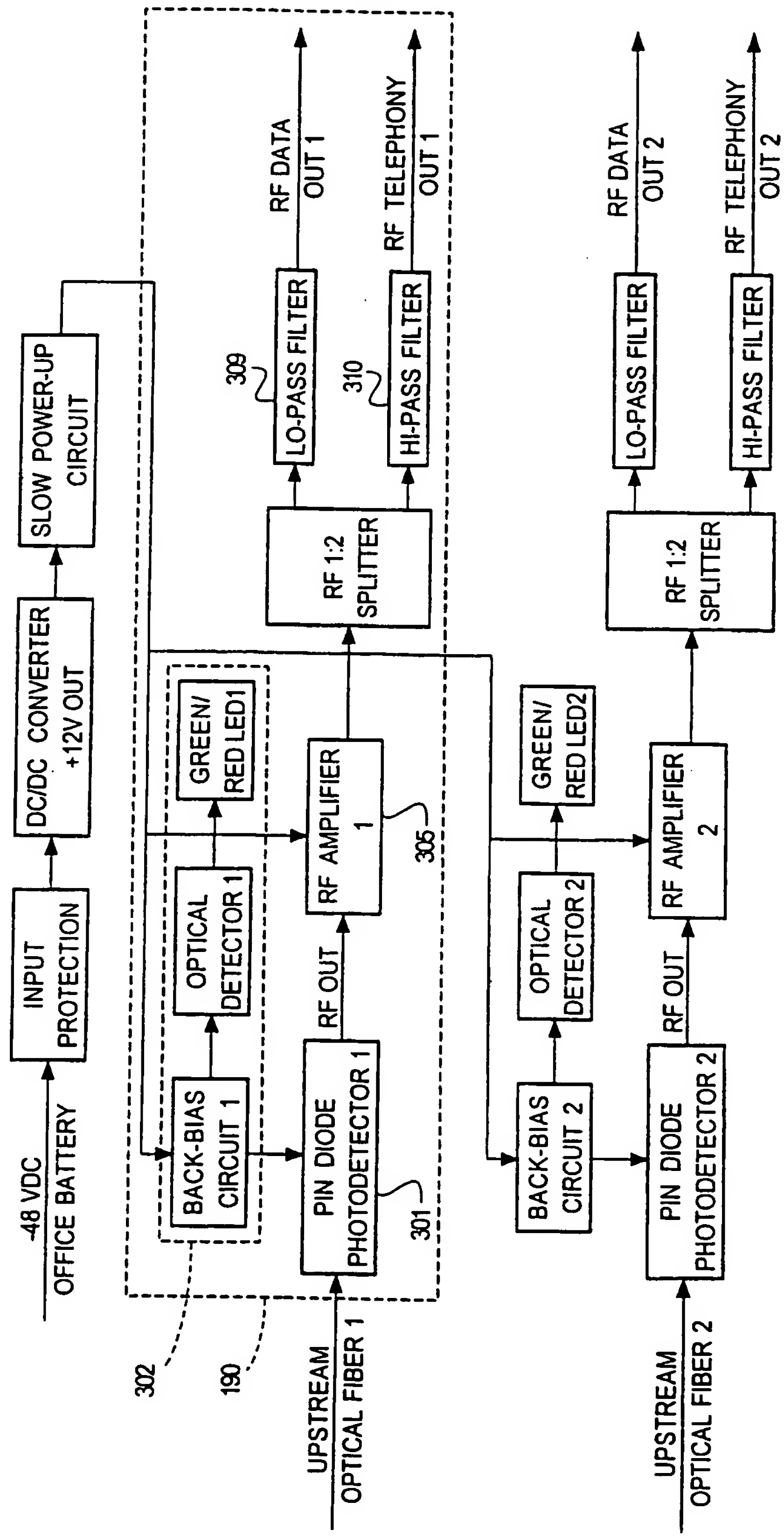
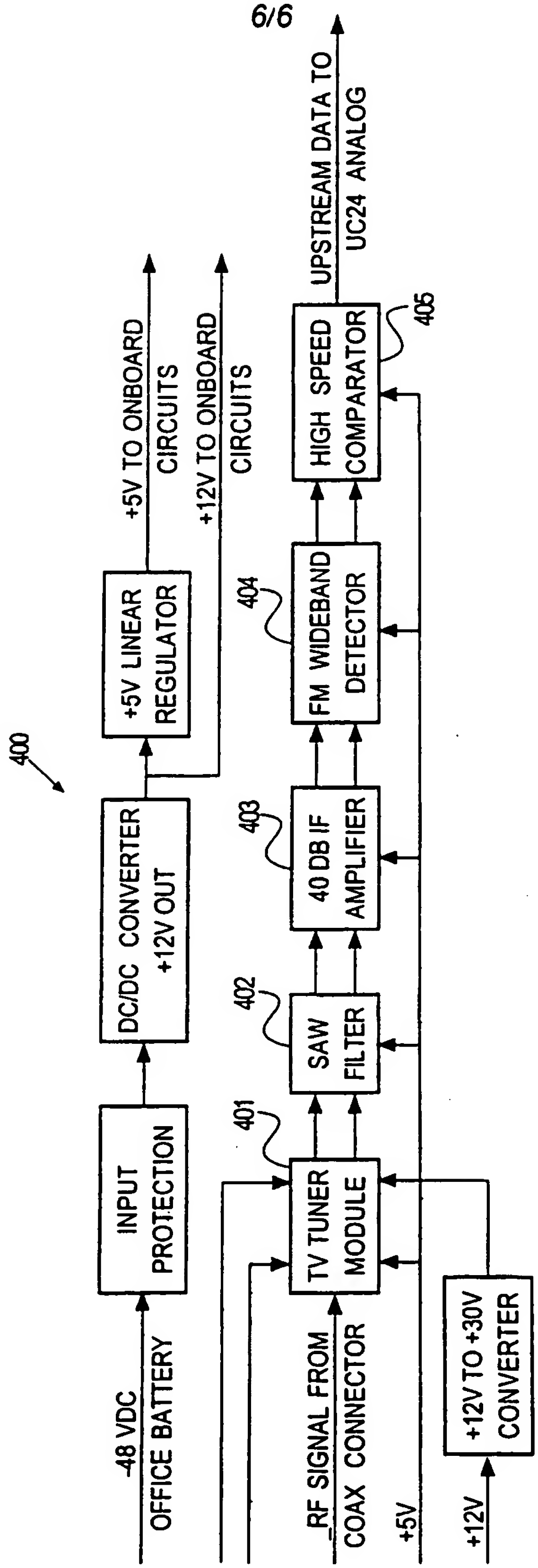

-48 VDC
OFFICE BATTERY
INPUT PROTECTION
DC/DC CONVERTER +12V OUT
SLOW POWER-UP CIRCUIT
BACK-BIAS CIRCUIT 1
OPTICAL DETECTOR 1
GREEN/ RED LED1
PIN DIODE PHOTODETECTOR 1
RF OUT
RF AMPLIFIER 1
RF 1:2 SPLITTER
LO-PASS FILTER
HI-PASS FILTER
RF DATA OUT 1
RF TELEPHONY OUT 1
309
310
305
301
302
190
UPSTREAM OPTICAL FIBER 1
BACK-BIAS CIRCUIT 2
OPTICAL DETECTOR 2
GREEN/ RED LED2
PIN DIODE PHOTODETECTOR 2
RF OUT
RF AMPLIFIER 2
RF 1:2 SPLITTER
LO-PASS FILTER
HI-PASS FILTER
RF DATA OUT 2
RF TELEPHONY OUT 2
UPSTREAM OPTICAL FIBER 2

FIG. 6


400
-48 VDC
OFFICE BATTERY
INPUT PROTECTION
DC/DC CONVERTER +12V OUT
+5V LINEAR REGULATOR
+5V TO ONBOARD CIRCUITS
+12V TO ONBOARD CIRCUITS
RF SIGNAL FROM COAX CONNECTOR
+5V
+12V
+12V TO +30V CONVERTER
401
TV TUNER MODULE
402
SAW FILTER
403
40 DB IF AMPLIFIER
404
FM WIDEBAND DETECTOR
405
HIGH SPEED COMPARATOR
UPSTREAM DATA TO UC24 ANALOG